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Book review

S. Wolfram, A New Kind of Science, Wolfram Media, 2002.

Wolfram's New Science: A New Start?

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1. Introduction

When I was a graduate student in physics a few decades ago, I heard about Stephen Wolfram through his newly released product, *Mathematica*. Though it was similar to other products on the market, my curiosity about it rose after I attended a talk about an add-on package for the program. The speaker demonstrated the use of the package to carry forth laborious (400 page worth) Ricci tensor computations for a General Relativity problem. I recall wondering at the time if I was witnessing the beginning of an era where symbolic math manipulations would be completely taken over by computers—freeing physicists to pursue more creative uses of their time. Though such an era has not yet arrived, as I look back I can say that his program was an inspiration in my own research.

In his recent book "A New Kind of Science" (NKS) Wolfram presents—along with a discussion of cellular automata—the belief that a computing framework closely tied to perceptual analysis, not to a symbolic framework may ultimately be the preferred modeling language for reality. Since NKS has been in print for some time now, there already have been a number of reviews; many have been critical of his claims that cellular automata have something new to offer the physical sciences. Most reviews, however, have not focused upon the significance of Wolfram's discussion for AI.[1]

2. Background on cellular automata and Wolfram

Cellular automata are a relatively new computational paradigm—originating with Turing's work in 1936 on reproducing Gödel's results as applied to the Entscheidungsproblem

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of Hilbert. In this famous problem, it is asked whether or not a general (or 'universal') algorithm exists that can decide the truth of an arbitrary first-order logic statement. It is closely related to the Halting problem, i.e., determining whether or not any algorithm will stop in a finite amount of time. Although Turing showed that no such universal algorithm exists, its consideration led him to introduce the notion of a Turing machine and in particular a universal machine for computations.

Motivated by Ulam, Von Neumann in the 1950s used cellular automata in his examination of self-replicating machines. Later work was done by Burks and Holland and others in the early 1960s which is featured in the book by Burks, "Essays on Cellular Automata". Cellular automata are perhaps best known to the public through the work of Conway, whose 1970 "Game of Life" consists of a 2-D grid of colored squares where future states depend upon the colors of the squares surrounding them. Then, in the mid 1970s, Mandelbrot developed the idea of fractals, demonstrating the importance of associating computations with perceptual information encoded via computer graphics. Wolfram started his studies of 1-D automata in the early 1980s which eventually lead him to a more detailed study for the book.

Stephen Wolfram was something of a child prodigy, receiving his Ph.D. in physics in 1979 from CalTech at age 20. Among other distinctions, he received the McArthur Prize Fellowship in 1981 for his work in particle physics. Later, in 1986 while at the University of Illinois at Urbana-Champaign, he began to develop the algebra expert system known as *Mathematica*. A few years later he founded Wolfram Research, which continues to extend *Mathematica* and to market it with considerable success. Readers may also know Wolfram Research as the sponsor of a math encyclopedia *MathWorld*, which is hosted at the company's web site.

3. An overview of the book

In some respects, this book could simply be viewed as an attempt to raise the market awareness of *Mathematica*; however to my delight what I found at the core of Wolfram's effort was a sincere attempt to investigate some fundamental questions for science and philosophy. Such questions involve the fundamental nature of complexity in the natural world: e.g., how did complexity emerge (through Big Bang evolution for example) from something that ultimately may have had little if any structure? Another related question involves the exact composition of the physical laws that we observe: Is there a unique set of such laws (involving forces, matter and energy, as well as space-time topology) that are required in order to generate the rich complexity we associate with the natural world? To what extent is the time-evolution of the world deterministic? And so on.

Wolfram prepares the reader for the magnitude of the book by explaining that from his early investigations with 'simple programs', a phrase he interchangeably uses with automata, he was inspired to investigate their properties more systematically to understand fundamental questions regarding complexity. On page 51 he writes:

> "Is it only cellular automata with very specific underlying rules that produce [complex] behavior? Or is it in fact common in all sorts of simple programs? My purpose ... is

to answer this question by looking at a wide range of different kinds of programs. And in a sense my approach is to work like a naturalist—exploring and studying the various forms that exist in the world of simple programs."

The book is divided into two major parts. The main text—of 12 chapters and about 700 pages–is written in a fashion that is somewhat reminiscent of the posthumously published notes of Buckminster Fuller due to the large number and variety of illustrations—many of them geometrical patterns—and because of its almost obsessional focus at times on painstaking details. Some illustrations are computer generated with automata models; others are illustrations of a particular automaton.

The Notes sections at the back of the book (almost 400 pages) correspond to each chapter. Here, references to past work and a variety of topics not covered in the main section are discussed. Included are many automata models expressed as statements that can be entered into *Mathematica*. Presumably this is why the book is divided in this fashion, to serve both as an inspiration for someone newly acquainted with cellular automata as well as a reference for someone doing research. Historical accounts of various topics of research can be found here although additional information can also be located on Wolfram's website: http://www.wolframscience.com.

Of the 12 chapters, the first three are introductory, setting out his notion of a "naturalist" methodology in some detail; the next six present a very wide range of applications (to math, biology, physics, and the other sciences); and the last three chapters sound out some philosophic consequences. For example in Chapter 3, *The World of Simple Programs*, Wolfram discusses a number of automata paradigms, such as substitution systems, Turing machines, and tag systems at a level that is not overly technical. In Chapter 6, *Starting from Randomness*, he discusses how simple programs can be used to create order starting

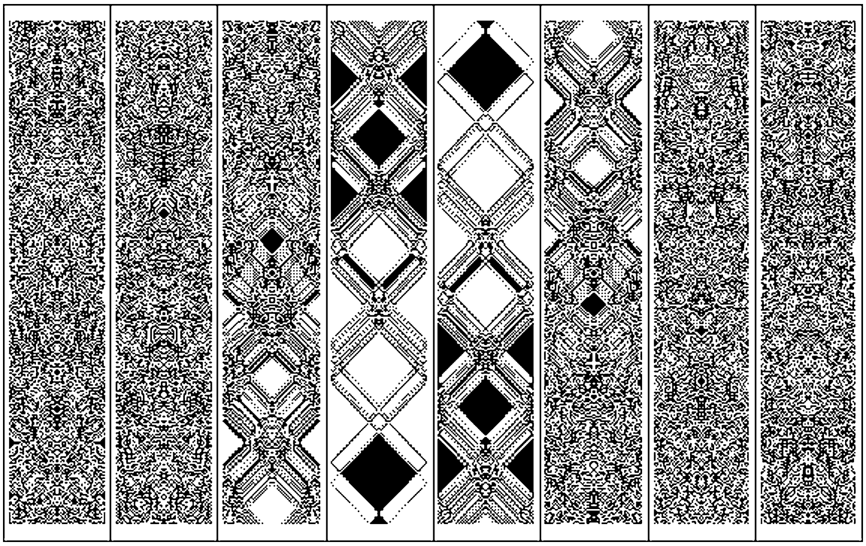

Fig. 1. An illustration from Chapter 9 on Fundamental Physics demonstrating a reversible algorithm.

with random data as well as generate randomness out of order. In Chapter 9, *Fundamental Physics*, you will find a discussion of causal networks, irreversibility and the 2nd law of thermodynamics, and time dilation in Relativity theory. Many of these illustrated automata models are available on the accompanying CD for the reader to test out. An automata browser is provided that is convenient to use.

In discussing his systematic approach towards generating and observing various automata models, Wolfram's focus is not upon succinct symbolic descriptions that could be used as part of proving theorems. Instead, he tells the reader early on that most interesting phenomena are too complex for the former, even though they do tend to be based on simple rules. Wolfram ran many hundreds of thousands of experiments in which he observed many cellular automata rules at work; to do this he needed the help of programs to identify certain characteristics he was looking for. This painstaking process took him over 10 years of work, as he explains in the preface and Chapter 1, and all of this effort led him to several conclusions which are discussed in the last three chapters of the book.

Of particular interest to the AI community are his ideas in Chapter 10 on *Perception and Analysis*. Here, he formally recognizes the brain/mind/observer as the key player in defining his notion of complexity. Wolfram also justifies his brand of naturalism by suggesting that the universe itself might be an enormous cellular automaton—a notion in line with speculations of Feynman and Fredkin among others. Such a view suggests the eventual clash between two competing foundations for physics: (1) elegant math, as in the standard model for particle physics and cosmology, and (2) an automata approach rich with visual-based representations of a variety of complex phenomenon. The tradeoffs between using both approaches, i.e., the neat, yet sometimes complex summarization capabilities of mathematics for simple systems, verses the simplicity and tractable expressions of complex systems found in automata models are discussed at several points in the book. More on these various topics will be presented later in the review.

4. Elementary cellular automata and rule 110

Many reviewers of Wolfram's book have noted his discussion of 'rule 110' due to its importance to the concept of universal machines. Before discussing this, some background is given on the concept associated with elementary cellular automata. To begin with, one does not need to invoke mathematics to describe automata. This fact reflects upon one of Wolfram's core beliefs, i.e., that science as expressed within the framework of traditional mathematics is too limited, too concerned about numerical analysis and the sizes of numbers. As he states on page 116:

> "One might think that with all the mathematics developed for studying systems based on numbers it would be easy to answer [questions about complexity]. But in fact traditional mathematics seems for the most part to lead to more confusion than help. One basic problem is that numbers are handled very differently in traditional mathematics from the way they are handled in computers and computer programs. For in a sense, traditional mathematics makes a fundamental idealization: it assumes that numbers are elementary objects whose only relevant attribute is their size."

Then, later in Chapter 10 on page 607 he adds:

> "The crucial idea ... is to think about numbers not in terms of their size but instead in terms of their digit sequences."

In Wolfram's view, a new science is needed for a deeper appreciation of the natural world—lurking somewhere within the automata models he discusses. This is because automata represent the more general notion of pattern dynamics. With particular regards to his investigation of the expression of complexity in models about the natural world, his beliefs are definitely justified.

Consider, for example, the following three-cell rule set:

■ ■ □	■ □ □	□ □ ■	□ ■ ■
□	■	■	□

Here, rules that do not explicitly generate a change of state for a cell are not represented. The top row of each of the four patterns shown represents the initial pattern, or part of a generation, that might exist in a cellular array. The solitary cell shown below the three-cell pattern represents the next generation cell state corresponding to the center cell above it. Now consider applying these rules to the following four-cell array. The array is wrapped around a cylinder to remove the considerations of boundary conditions. Hence the left side of the array is considered to be adjacent to the right side.

■	□	□	■
□	■	■	□
■	□	□	■

Upon applying the pattern dynamics embedded in the rules, it is seen that the third generation turns out to be identical to the first generation, thus establishing a predictable pattern for each subsequent generation. This would have been the case for an infinitely wide array of cells as well, only the predictable patterns would have propagated to include more cells with each generation. According to Wolfram's empirical study, such predictability is easy to find within cellular automata rule sets. To address the question about expressions of complexity in rule-based systems, however, it was necessary to create a systematic method of discovering rule sets that generate patterns that aren't easily predictable.

To sweep across all possible rule sets for three-cell patterns, Wolfram indexes them using binary arithmetic. Wolfram isn't this explicit in stating what he is doing so the reader has to do some careful reading between the lines. Below is one of 256 rules that exist for three-cell patterns. Here it is seen that all possible three-cell patterns are represented in the rule. Any particular rule is identified by the bit pattern formed from the single cell states. Thus the bit pattern for this rule is 01101110—a 0 for white and 1 for black—which is binary for the base 10 number 110.

■ ■ ■	■ ■ □	■ □ ■	■ □ □	□ ■ ■	□ ■ □	□ □ ■	□ □ □
□	■	■	□	■	■	■	□

This rule turns out to generate the most complex category of patterns that Wolfram discusses. The highest complexity that one observes in automata systems is represented by patterns that resemble irrational numbers, i.e., numbers that have no discernible closed form numerical representation yet posses a mixture of some order with apparent randomness. For such systems, there can be no shortcuts to predicting the evolution of the system other than to explicitly carry forth computations with the rules from one generation to the next. This is talked about by Wolfram in terms of the 'communication' that exists between generations of automata that display high complexity. As he writes on page 252:

> "A characteristic feature of [complex systems] is that they show long-range communication of information—so that any change made anywhere in the system will almost always eventually be communicated even to the most distant parts of the system ... [For other systems] long-range communication of information is in principle possible, but it does not always occur—for any particular change is only communicated to other parts of the system if it happens to affect one of the localized structures that moves across the system."

Wolfram introduces other automata paradigms where the basic rule mechanism behind elementary cellular automata is replaced by something more complicated. The reason for considering such paradigms is due fundamentally to one basic premise: cellular automata represent only one type of rule base—one that applies universally across all cells. Other paradigms introduce inhomogeneity in the rule base, either in terms of how the rules apply across generations or where they occur within a given generation.

5. Complexity

Intermixed in the discussion of various automata models are statements that express Wolfram's perspective on the importance of finite automata. Consider the following statement that he makes on page 368, in Chapter 8 on *Implications for Everyday Systems*:

> "One might have thought that in the literature of traditional science new models would be proposed all the time. But in fact the vast majority of what is done in practically every field of science involves not developing new models but rather accumulating experimental data or working out consequences of existing models ... And among the models that have been used, almost all those that have gone beyond the level of being purely descriptive have ended up being formulated in very much the same kind of way typically as collections of mathematical equations. Yet as I emphasized ... this is, I believe, the main reason that in the past it has been so difficult to find workable models for systems whose behavior is complex. And indeed it is one of the central ideas of this book to go beyond mathematical equations, and to consider models that are based on programs which can effectively involve rules of any kind."

This is a bold statement by Wolfram which summarizes his belief that cellular automata represent a "new" science. Yet, in terms of implementation, cellular automata can be represented mathematically by iterative processes occurring among a set of variables, and thus one can ask to what extent this is a departure from traditional methods. It is really only the geometrical component, designed to help the researcher to identify patterns, which is layered upon the automata that adds something new. As discussed in the section on Perception in this review, Wolfram suggests that it is this inspection process that is largely responsible for determining the degree of complexity that exists. However, there are other measures of complexity. One in particular is the topic typically discussed in computer science involving the amount of effort required to compute a solution to a problem. This analysis is mathematically based and not the type of empirical science that Wolfram seems to suggest that we need.

It is clear, however, that finite automata add a useful simplification to the analysis of the varieties of problems we encounter in everyday life. Wolfram points this out effectively in Chapter 8. Here, one can find topics such as the growth patterns in biological organisms, economic theory, turbulence in fluid flow, and nucleation in crystal growth. As with other discussions within the text, Wolfram demonstrates how cellular automata models can be used for modeling most anything. This includes the examination of mathematical computations itself. In the Chapter 4, *Systems Based On Numbers*, he discusses the patterns that develop in arithmetic operations, trigonometric functions, and iterated maps that lead to chaos phenomenon—demonstrating how they resemble patterns of simple programs. However Wolfram only briefly mentions the consideration of continuous number representations. He tells the reader why this is the case on page 168:

> "With all the work that was done on continuous systems in the history of traditional science and mathematics, there were undoubtedly many cases in which effects related to the phenomenon of complexity were seen. But because the basic phenomenon of complexity was not known and was not expected, such effects were probably always dismissed as somehow not being genuine features of the systems being studied. Yet when I came to investigate discrete systems there was no possibility of dismissing what I saw in such a way. And as a result I was in a sense forced into recognizing the basic phenomenon of complexity."

Here it isn't clear what Wolfram refers to as the basic "phenomenon" of complexity and why it was "not known" however it is likely that he is referring to studies with nonlinear dynamics that lead to chaos theory. In this branch of physics, real-number analysis of physical systems is replaced by slices of time and grids within state-space (i.e., all possible values within a certain uncertainty that the dynamical variables of the system can acquire). With this transposition of a continuous representation to a discrete representation, much of the "complexity" within everyday physical systems becomes easier to see.

Before finally defining complexity directly on page 559, Wolfram points out a definition of randomness that is distinct from other definitions such as the notion that a random sequence is one that has no short description for it. Here he states on page 557:

> "... something should be considered to be random whenever there is essentially no simple program that can succeed in detecting regularities in it."

He then makes an interesting definition of complexity on page 559 that demonstrates his and the subjective perception of it:

> ". . . as a practical matter, by far the most common way in which we determine levels of complexity is by using our eyes and our powers of visual perception. So in practice what we most often mean when we say that something seems complex is that the particular processes that are involved in human visual perception have failed to extract a short definition."

I find this definition to be quite intriguing. Among other things, it suggests the need to explore ties between human visual perception research and automata modeling.

In Chapter 11 on *The Notion of Computation*, Wolfram returns the discussion of automata back to its roots. Here, he prepares the reader for a discussion on a universal algorithm. As he states on page 643:

> "Despite its great importance in computing and elsewhere, it turns out that universality has in the past never been considered seriously in relation to natural science . . . [however] universality is . . . crucial in finding general ways to characterize and understand the complexity we see in natural systems."

Wolfram is correct in that explicitly, as stated, universality has not been considered in natural science before. However, in terms of the goal associated with universality, it is very similar to the problem of unification for the laws of physics. The laws, as commonly expressed on their own require different types of mathematical manipulations depending upon the system under study. For example, Maxwell's original laws of electromagnetism are known to most as four separate laws involving ordinary derivatives, divergences and curls. However upon casting these separate laws into a relativistic covariant form using four-vector notation, one elegant computational framework can be applied regardless of who is observing the physical system or what electromagnetic forces are present. Further transformation into a quantum field theory framework using a four-vector potential casts the representation into a form that is amenable to unification with the short-range weak and the strong forces. Today, the search is still on for a tractable form of computation that includes gravitational interactions.

The same concept applies to universal machines. Computer languages are based upon a fixed set of instructions that can be combined in arbitrary sequences to perform computations with a central processing unit. A universal machine, which describes most computers, refers to a special instruction set that can be used to implement any algorithm (computation) that we can articulate in finite terms. An irreducible, universal set of instructions, in a sense, provides us with a unified computational framework for algorithms, just as the fundamental laws of nature expressed in a unified framework provides us with a unified computational framework for simulating a physical system. The fact that physicists are struggling to unify gravity with the other forces is synonymous with saying that they are struggling with defining algorithms that can be articulated in finite terms, i.e., shown to halt, even with approximation methods.

6. The classification of automata

As mentioned, there are a variety of cellular automata paradigms that Wolfram discusses. Differences between these paradigms involve such considerations as the use of colors, connectivity, as well as varying the regions of active evolution. Regardless of the rule paradigm that is adopted, Wolfram suggests that all conceivable patterns generated by cellular automata can be grouped into one of four fundamental classes. The first two classes ultimately lead to an evolution of the system that achieves a steady-state behavior even though initially the evolution may be difficult to determine. Class 3 rule sets have significantly higher complexity, with some randomness although within a short span of generations it is relatively easy to predict what patterns will emerge. Class 4 rule sets, which include rule 110, involve the highest degree of complexity found whereby both randomness and chaos emerge in a cooperative fashion to create intricate structures.

In terms of utility, this classification scheme presents the author (and the reader) with a label to attach to a particular computation. However, one can say that a cellular automata framework doesn't have to be invoked to devise this classification scheme for physical systems. We know from analysis in physics that systems

(1) may stop evolving,
(2) reach steady-state equilibrium that could exhibit various types of periodicity,
(3) evolve predictably with some noise or interaction with other systems or
(4) evolve in ways that embrace both chaos and order.

The reason Wolfram introduces it, however, is that it prepares the reader for further discussion on the universality of computation.

Upon reading the book it is clear that only algorithms exhibiting the most complex behaviors, i.e., Class 4 automata, can be considered as candidates for a universal machine. However Wolfram goes further and writes on page 691:

> "I strongly suspect that it is true in general that any cellular automaton which shows overall class 4 behavior will turn out—like rule 110—to be universal."

Not all Turing machines are Class 4 type, and as such it is somewhat straightforward to use empirical methods to rule a large number of them out as candidates—according to Wolfram this applies to all Turing machine configurations with a number of states less than 4 and two colors for each cell. To theoretically prove that a particular computational paradigm is universal, however, it is necessary to show how the paradigm can be applied to reproduce the rule set of a system that is known to be universal. In particular the embedding of cyclic tag systems (shown to be universal by Minsky) within rule 110 is used to argue the rule's universality. Unfortunately for the reader, little exposition accompanies this presentation, even in the notes section.

7. Perception and AI

If perception is crucial to complexity, then perhaps so is thinking. This is one of the themes in the later philosophical chapters. In Chapter 10, Wolfram makes what may be among the most striking of his claims, and especially of most interest to readers of AIJ. In effect he argues that it may be easier to build general-purpose human-level intelligence than to build a narrowly constrained intelligence for a specific real-world task. He does not give examples, but it appears that he has in mind almost any of the standard AI tasks that we find so hard to solve, namely ones where the true dynamic uncertainties of the world are allowed to impinge, whether in coffee-making, or playing soccer, or even playing chess with a real chess board. He writes on page 629:

> "... on the basis of traditional intuition, one might ... assume that the way to solve this problem must be to use systems with more complicated underlying rules, perhaps more closely based on details of human psychology or neurophysiology. But from the discoveries in this book we know that this is not the case, and that in fact very simple rules are quite sufficient to produce highly complex behavior ... Nevertheless ... there may still be a problem. For insofar as the behavior that one gets is complex, it will usually be difficult to direct it to specific tasks—an issue rather familiar from dealing with actual humans. So what this means is that most likely it will at some level be much easier to reproduce general human-like thinking than to set up some special version of human-like thinking only for specific tasks."

This suggests that, if we were able to build a real-world coffee-making robot that performs on a par with humans, it would have to deal with uncertainties and surprises as well as humans (muddy water, no electricity, broken crock, a request for coffee instead at a later time, etc.); i.e., the frame problem in its full glory, and more, so that this particular skill becomes an AI-complete problem. But Wolfram has even more in mind when he says this will be harder than building general intelligence. To get it to perform as well as humans at coffee-making, it will need the apparent complexity of humans which in his view is built up from simple programs; yet it will be difficult to get a complex system to restrict its performance within only a narrow range (e.g., to only making coffee instead of walking the dog or riding a bike at the same time).

Here we see the results of his crucial experiment take hold in his thinking, i.e., that the apparent complexity of Class 4 automata must in some way be representative of the complexity that resides within us. This leaves the discussion open, then, as to how to get a system to exhibit the complexity needed to learn about the environment, yet possess the self-controlling behaviors necessary to narrow down this complex behavior when specific desirable tasks are required. Here he states his views on aspects of memory on page 626:

> "There are many kinds of similarities that we recognize quite effortlessly. But there are also ones that we do not. And thus, for example, given a somewhat complicated visual image—say of a face or a cellular automaton pattern—we can often not even immediately recognize similarity to the same image turned upside-down. So are such limitations in the end intrinsic to the underlying mechanism of human memory, or do they somehow merely reflect characteristics of the memory that we happen to build up from our typical actual experience of the world? My guess is that it is to some extent a mixture."

It thus seems Wolfram is hinting that experience plays a key role in reinforcing desirable behaviors within a complex system.

Wolfram's discussion provides an effective counterpoint to suggestions by Penrose in his own book, "The Emperor's New Mind" that consciousness is 'non-algorithmic'. Penrose makes his assertion as a reaction to the implication of Gödel's theorem that a mathematical system based upon a set of axioms is either logically inconsistent or incomplete. Upon viewing human intelligence and consciousness as unaffected by this limitation, Penrose speculates that there must be some as yet unknown properties associated with quantum mechanics.

Wolfram states that so far quantum mechanics introduces doubt about whether or not there is a fundamental limit in our ability to articulate all the processes of the natural world in a finite sense, including human intelligence. However he believes no such fundamental limit exists; preferring to adopt what is known as a "hidden variable" theory. As Wolfram writes on page 1126 in the notes section:

> "The validity of Church's Thesis has long been taken more or less for granted by computer scientists, but among physicists there are still nagging doubts, mostly revolving around the perfect continua assumed in space and quantum mechanics in the traditional formalism of theoretical physics. Such doubts will in the end only be put to rest by the explicit construction of a discrete fundamental theory along the lines I discuss ..."

A hidden variable theory suggests that there exist unobservable phenomena that impact the evolution of what it is we can perceive. Upon applying an explicit construction of such a theory within a computer that contains all the degrees of freedom of the universe one can replicate the workings of the universe according to Wolfram's thinking. Since a contradiction arises for the existence of such a large computer, however, ultimately one is left with the same conundrum that mathematical theorists are faced with, i.e., that of the need to find approximate methods to produce more compact finite representations of physical systems. Wolfram's variety of automata models demonstrates that such approximations may be well represented within the world of simple programs.

8. The Universe

In Chapter 12, Wolfram goes further than suggesting that cellular automata are simply good for modeling with a discussion on the concepts of computational equivalence, and irreducibility. The term 'computational equivalence' is usually reserved for computational architectures that can compute the same set of functions. Wolfram extends this use of the term to refer to any physical system. In essence, he is suggesting that physical systems as expressed within a grand unified automata model contribute in an equivalent fashion to the level of complexity associated with the model. As written on page 730:

> "... my strong suspicion is that at a fundamental level absolutely every aspect of our universe will in the end turn out to be discrete. And if this is so, then it immediately implies that there cannot ever ultimately be any form of continuity in our universe that violates the Principle of Computational Equivalence."

Later, Wolfram makes a statement that further describes the principle in such a fashion that it is reminiscent of a well-know consideration within quantum mechanics. As he states on page 736:

> "If one studies systems in nature it is inevitable that both the evolution of the systems themselves and the methods of perception and analysis used to study them must be processes based on natural laws. But at least in the recent history of science it has normally been assumed that the evolution of typical systems in nature is somehow much less sophisticated a process than perception and analysis. Yet ... once a rather low threshold has been reached, any real system must exhibit essentially the same level of computational sophistication. So this means that observers will tend to be computationally equivalent to the systems they observe—with the inevitable consequence that they will consider the behavior of such systems complex."

One of the biggest debates about quantum theory has centered on the asymmetry that exists between the observer and the system under observation. The asymmetry is paradoxical, i.e., as notably pointed out by Schrödinger with his cat in a box example. Upon adopting the view that ultimately all systems are universal, Wolfram is suggesting a method for removing such asymmetry. However in effect, this really is equivalent to the statement earlier in this review comparing the unification effort of the four fundamental forces to considerations for universal machines.

Though Wolfram steadfastly suggests that simple programs are the underpinning of all complex processes even with considerations of quantum mechanics, he readily admits that much work is needed to discover such modeling. As he writes:

> "In its development since the early 1900s quantum theory has produced all sorts of elaborate results. And to try to derive them all from the kinds of models I have outlined here will certainly take an immense amount of work. But I consider it very encouraging that some of the most basic quantum phenomena seem to be connected to properties like causal invariance and the network structure of space ..."

In tandem with the Equivalence principle, Wolfram introduces the notion of computational irreducibility, i.e., that much of what we consider to be complex involves processes that are not likely to have closed-form solutions. As he writes on page 748:

> "In the past it has normally been assumed that there is no ultimate limit on what science can be expected to do. And certainly the progress of science in recent centuries has been so impressive that it has become common to think that eventually it should yield an easy theory—perhaps a mathematical formula—for almost anything. But ... this can fundamentally never happen, and ... in fact there can be no easy theory for almost any behavior that seems to us complex."

This part of the discussion is reminiscent of the points made by Hofstadter in his book: "Gödel, Escher, Bach: An Eternal Golden Braid" in which he discusses the many paradoxes one encounters with the attempt to discuss closed-form representations for thought.

9. Other reviews

The lack of explicit references has caused some to suggest that Wolfram is unfairly taking credit for work that is not his own. In writing the book, it is likely that Wolfram considered it obvious that he cannot take credit for work that was published before his own. He seems to have largely addressed this criticism through his website, however his presentation would have been clearer if he had acknowledged other work in his actual discussion.

A more serious criticism questions the claim that cellular automata represent a new science that will lead to new insights and discoveries. This criticism is particularly noteworthy in such discussions as found in the section on Space, Time and Relativity (pp. 516–524). Here, Wolfram suggests that the discussion of Relativity theory with the use of a 'causal' network cellular automaton lends a better illustration of time dilation. There is no suggestion by Wolfram as to how cellular automata could be used to make the leap between this representation and the formula associated with time dilation. For reasons such as this, critics have suggested that Wolfram's 'new science' is the "Emperors New Clothes" in disguise that will add little if any value to scientific research.

I am reminded of a statement that Warren McCullough is credited with saying, "Don't bite my finger, look where I'm pointing." In Wolfram's defense, it has to be stated that cellular automata do represent a general computational framework in which to do simulations. As a mere computational engine, however, it doesn't add any particular value over other simulation methods based upon formal mathematical treatments. In essence this is what critics are referring to. Physical systems in general are represented by partial differential equations which sometimes involve integral expressions, matrices, and nonlinear expressions. Numerical simulation methods for these types of systems have been developed for years without cellular automata as an explicit paradigm for generating computations. However, my interpretation of Wolfram's discussion suggests that this well-known area of computational science is not where the 'new science' resides. Wolfram isn't suggesting a complete replacement for it either. Instead he suggests that it is a framework for new discovery, believing that ultimately, cellular automata modeling will be able to subsume the accomplishments of mathematics, rather than the other way around.

I suggest that the reader also look at other reviews such as those by Henry Cohn and Ray Kurzweil on the web. They notably attack his attachment to cellular automata though both recognize many of the important contributions he is making. In one particular comment, Kurzweil goes a little too far:

> "Although predetermined, the behavior of Class 4 automata cannot be anticipated (other than by running the cellular automata) and is effectively random. This is not a new view, and is equivalent to the "hidden variables" formulation of quantum mechanics, which states that there are some variables that we cannot otherwise access that control what appears to be random behavior that we can observe."

I think it is incorrect to suggest somehow that the Class 4 concept in its entirety has been thought of before. Wolfram clearly points to the importance of associating the concept with universal machines. Also, hidden variables are supposedly the simple programs themselves which could be Class 1, 2, 3, or 4 depending on the system under study.

Kurzweil also writes:

> "If Wolfram, or anyone else for that matter, succeeds in formulating physics in terms of cellular-automata operations and their patterns, then Wolfram's book will have earned its title."

Though physics is predominantly mentioned in Wolfram's book, it isn't the only science Wolfram has in mind. In particular, there are several directions for cellular automata modeling to take, including the human mind as Wolfram mentions briefly. However on the topic of mathematics, he is openly biased against discussing it since he believes it should be replaced in the study of complex systems. Henry Cohn displays his dissatisfaction with Wolfram's insistence on this point, in particular in his avoidance of discussing problems which he calls "intermediate", i.e., not as difficult as the Halting problem, but still unsolvable:

> "Wolfram's Principle of Computational Equivalence amounts to a very strong rejection of these intermediate problems. He acknowledges that they exist (p. 734), but more or less dismisses them as contrived (because they are complicated and formed by explicitly weakening more powerful systems), and seemingly asserts that they will almost never come up, in randomly chosen systems or ones observed in nature."

Admittedly, Wolfram isn't addressing theorem proving in his book and so there isn't a discussion about the appearance of such intermediate problems in automata evolution by random chance. Cohn's remarks seem to be triggered by Wolfram's statements suggesting that ultimately all physical entities will be shown to be universal algorithms within a grand automata model. Cohn wonders why Wolfram restricts his hypothesis to only this level as opposed to suggesting that lesser forms of hard problems would also be seen. Perhaps here Cohn is expressing the classic Platonic view that mathematics of all kinds ultimately expresses itself in reality. However as discussed earlier, Wolfram is hinting at the importance of retaining symmetry between the observer and the observed and his notion of universality fits this requirement.

10. A new start?

After adopting a fundamental shift in perspective about the utility of symbolic manipulation, Wolfram has spent a considerable number of years to convince others to set upon a new course for modeling the natural world using automata. Perhaps the most intriguing possibilities associated with automata have to do with the ultimate analysis that we may want to perform about the natural world, namely models of intelligence. This topic isn't addressed adequately by Wolfram's book, but in a sense, this is where several sciences seem to be heading. Upon looking at the history of physics alone, the scientific quest for knowledge has traditionally looked outwards towards describing objective reality. However, particularly noteworthy in the 20th century are more inward-focused attempts to describe it. For example, Einstein's Relativity work can be viewed as a subtle recognition of the subjective nature of observations. Quantum physics introduced an even more bizarre recognition of this subjective nature by questioning the determinant nature of the information collected from measurements. Such subjectivity might have its ultimate expression within the mind.

Mathematics is a construct of the mind, and represents grounding for much of our scientific understanding; however it is my belief that cellular automata represents the working of the mind more closely than mathematics. I would not go so far as to suggest, as Wolfram does, that this also applies to the dynamics of the natural world. It is clear that the overall theme of Wolfram's 'new science' represents an attempt to replace the mathematical foundations in physics with our modern era's computational philosophy. Yet the work of Godel, Church, and Turing demonstrate that there are clear problems with our thinking about computations. Finding the unique combination of rules which generate or encode a wealth of complexities as well as decode these complexities upon observations represents a Holy Grail for many of the sciences. As Wolfram would agree, the difficulty associated with the development of such models isn't due to the fact that simple rules don't exist, but rather to the difficulty for finding general methods for extracting such rules from observation. In my view, this is precisely the direction where a new science needs to go. Wolfram's discussion demonstrates that cellular automata provide an important investigative framework for such work.

Overall, it seems to me that Wolfram's proclamation about the limits of symbolic manipulation is largely justified, however just as finite automata represent approximations to the real world, so mathematics can be used to represent the impact of such approximations. Clearly, both frameworks provide something the other cannot. Ultimately this is a reflection upon our lack of ability to adequately transcribe our descriptions of reality between the two realms.

Further reading

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